Optical Imaging Device Designs for Solar-Powered Flight and Power Generation

The present invention relates to optical imaging arrangements. These include, in particular, arrangements that (1) are of very low mass per unit aperture area and which may have application

5   to facilitate solar-powered flight (including space flight) via direct deflection of sunlight, via solar thermal propulsion or via the generation of electric power that is then used to generate thrust; (2) arrangements which may be used to facilitate the generation of electric power from sunlight for terrestrial purposes; and (3) arrangements adapted to facilitate other applications envisaged in the applicant's previous patent application PCT/GB01/01161 entitled "Ultra-high resolution imaging

10   devices".

The present invention provides methods of designing optical imaging arrangements comprising at least two mirror surfaces, as defined in Claim 1, and devices incorporating optical imaging arrangements constructed in accordance with the methods claimed. The methods are developments and adaptations, which build on the original basic principles described in

15   PCT/GB01/01161.

(1)   An arrangement according to the present invention can provide thrust by concentrating sunlight. The invention may be implemented in a variety of adaptations.

(a)   Arrangements according to the present invention may be used as a "solar sail". In weightless conditions in outer space far from any planetary atmosphere it is possible to accelerate

20   a vehicle by direct deflection of light. This is possible because individual photons of light possess momentum (proportional to their energy and hence frequency), pointing in the direction in which the photon is travelling. Thus the act of deflecting sunlight imparts momentum to the deflector (and to any vehicle attached to it). In practice any such solar sail can be expected to be hundreds of square metres in size, or larger. Although the acceleration available from such a sail is small (if the

25   energy source is sunlight), it can operate continuously over long periods without using any internal fuel supplies. Therefore space vehicles powered by solar sails can, in principle, build up relatively high speeds. NASA seriously investigated solar sails in the 1960's as a possible means of achieving manned transportation around the solar system. It was even suggested that very high power lasers could be used instead of sunlight to propel a solar sail, increasing substantially the

30   acceleration available and potentially facilitating interstellar travel. Actual test sails proved less encouraging, although recent advances in ultra-lightweight mirror fabrication technology mean that organisations such as NASA, Team Encounter and the Planetary Society are planning launches of space vehicles powered by solar sails in the next year or two. Traditional solar sail designs involve an approximately planar sail surface. Unless the sail is fantastically light, altering the orbit in which

35   the vehicle travels around the sun requires the sunlight to be deflected in such a way as to provide thrust with a component perpendicular to the direction of the sun. Ideally a planar solar sail should be positioned so that the angle between the sun and the perpendicular to the sail surface is about 35.3°. This means that the surface area of a traditional solar sail has at least approximately 23% more surface area than the cross-section it presents to the incoming sunlight. Arrangements

according to the present invention can reduce this cross-sectional disparity, down to perhaps 5% or lower, thereby offering mass and hence cost advantages over traditional solar sail designs. Moreover, the calculation from which the 35.3° figure is derived, itself contains some compromises, since the trajectory change created by any given photon is maximised if the photon is deflected

5   through about 90° (which arrangements according to the present invention would permit for most photons striking it) rather than the 70.6° deflection supplied by such a positioning of a traditional solar sail. This compromise is not needed with arrangements according to the present invention, resulting in a further approximately 5% benefit over traditional solar sail designs. However, in arrangements according to the present invention, each ray of sunlight would be deflected three

10   times rather than the once applicable to a traditional solar sail design. As practical mirrors do not have 100% reflectivity, there would therefore be a small relative loss in efficiency because of the extra reflections.

        (b)   Alternatively, arrangements according to the present invention may be adapted to concentrate sunlight so as to heat up some propellant that would then be expelled in much the

15   same way as occurs in a rocket or jet engine. An advantage which may be obtained using such arrangements according to the present invention is the ability to concentrate sunlight to almost the maximum possible temperature without contravening the Second Law of Thermodynamics, i.e. to close to the temperature of the sun's photosphere (circa 5800K). This temperature is higher than any typically available via chemical rocketry (indeed it is so high that one might need to limit the

20   actual temperature to which the sunlight is concentrated to avoid melting whatever material was used to house the engine chamber, i.e. to keep it below probably circa 3700K, this being close to the melting point of tungsten or carbon). Hydrogen is probably the optimal rocket propellant to use because it has the lowest molecular mass of any gas, and hence provides the highest specific impulse (although if it is desired to avoid the use of inflammable propellant then helium might be a

25   useful alternative). A high specific impulse increases the thrust available per unit mass of propellant. In the atmosphere, the propellant gas could of course be air, which would eliminate the need for the vehicle to carry any propellant. The specific impulse of such a "solar thermal" propulsion arrangement, limiting the temperature as above, might be as high as circa 1000 seconds (or perhaps higher, see below), versus the 450 seconds delivered by a liquid

30   hydrogen/liquid oxygen chemical rocket as used by, say, the NASA space shuttle), i.e. with the hydrogen being expelled at circa 10^4 ms^{-1}.

        Solar thermal propulsion has been proposed for the Solar Orbit Transfer Vehicle (SOTV), an experimental design developed fairly recently by Boeing under a $48m contract from the US Air Force Research Laboratory, Kirtland Air Force Base, New Mexico. The SOTV envisaged

35   concentrating sunlight using parabolic mirrors into a cavity in which hydrogen gas was heated to circa 2300K, achieving a specific impulse of 750 to 850 seconds. In principle, sunlight can be concentrated using arrangements according to the present invention to a significantly higher temperature, increasing the specific impulse, and hence reducing the required propellant mass and probably the mass of the rocket engine (because it can be smaller). The surface area of a mirror

40   arrangement according to the present invention can be expected to be materially smaller than the

surface area of the mirror arrangement envisaged by NASA for the SOTV (considering the images and information presently available from NASA).

In the vicinity of the earth, arrangements according to the present invention would concentrate sunlight onto an area that was roughly 1/40,000th of the surface area of the mirrors,

5   into which the propellant would be injected at high pressure and heated. An advantage of solar thermal propulsion is that the specific impulse it delivers can be varied in a controlled way anywhere between close to zero and the relevant upper limit (probably circa 1000 seconds for the present invention, but see below), by lowering the temperature to which the propellant is heated (e.g. by increasing the flow of propellant through the engine) and hence lowering the speed with

10   which it is ejected. It should in principle also be possible to achieve an even higher specific impulse from a solar thermal propulsion arrangement than that referred to above by further heating the propellant downstream of the rocket or jet chamber. Like chemical rocket engines, conventional jet engines work by expelling gas that has been heated by a chemical reaction. The main conceptual difference is that they burn oxygen sourced from the air rather than stored within the vehicle. A way

15   of increasing the thrust of a jet engine is to include "after-burn", i.e. to ignite more fuel downstream of the air intake and compressor. This increases the speed at which the propellant is ejected. Typically it is not energy efficient to do this so afterburners are generally confined to military jets and used only when added thrust is particularly helpful. In a classical chemical rocket or solar thermal engine, the propellant is heated to a high temperature and pressure in the equivalent of the

20   combustion chamber. The gas then passes through a narrow rocket throat and subsequently expands as it passes through the rocket nozzle, gaining ejection speed as it does so. The nozzle needs to allow the gas to be expelled without obstacle, as to do otherwise would reduce the ejection speed. However if it were possible to heat the gas during this expansion phase without introducing obstacles to its free flow, then this would allow the gas to expand further increasing the

25   ejection speed. This might be achievable if the nozzle were itself long and at a high temperature and so radiated energy into the expanding gas. This may be facilitated by embedding most of the nozzle, possibly in a spiral shape, within a slab of material onto which the sunlight was being concentrated. The introduction of trace heat absorbent substances into the heated gas may then improve the radiative heat transfer from the nozzle sides to the gas within.

30   (c)   Further arrangements according to the present invention may be used to concentrate sunlight and to convert this energy into electric power. Vehicle thrust could be indirectly provided by consumption of this electric power. The very high temperatures to which the arrangements according to the present invention can concentrate sunlight permit some relatively unusual approaches to converting sunlight to electric power, for example via thermionic,

35   thermoelectric or closed cycle heat engine electric power generation. Of particular interest is the potential coupling of this sort of concentrator with thermionic power generation. Thermionic power generation is only practical at very high temperatures (which arrangements according to the present invention can deliver, see above). It permits a very high rejection temperature and, in principle, should require a relatively low mass per unit of electric power generated. For aeronautical

40   or astronautical applications, the larger the power output the more likely thermionic power generation is to be cost effective in comparison with solar photovoltaic arrangements according to

the US National Research Council Committee on Thermionic Research and Technology: "Thermionics Quo Vadis? An assessment of the DTRA's Advanced Thermionics Research and Development Program", National Academy Press (2001). According to this assessment, thermionic power should be able to provide conversion efficiencies of at least 20 to 25% if the input temperature was 2000K and the output temperature was 1100K (which is pretty high considering that the maximum possible efficiency it could deliver whilst not contradicting the Second Law of Thermodynamics given these input and output temperatures is (2000-1100)/2000 = 45%). Higher efficiencies should be possible if the input temperature was closer to those achievable using arrangements according to the present invention (up to circa 3700K). Alternatively, if an arrangement according to the present invention were to be used in a manner adapted for solar thermal propulsion, a suitable liquid or gas might be injected into a heat exchanger at the focal point of the arrangement, but instead of being expelled to provide thrust, it might be recycled via a closed heat engine to generate electric power. Ways of creating thrust from electric power generated in these (or other) fashions include:

- In air, the electricity thus generated might be used to drive propellers or to provide a heat source for the equivalent of a jet engine. The optical arrangement may, for eample, be embedded within a transparent inflated balloon, with the balloon providing uplift and rigidity and with propellers used to control where the vehicle went. Such a vehicle may thus be able to stay indefinitely in approximately the same position in the air (a potentially desirable characteristic if the vehicle were being used as, say, a radio base station for communications purposes).

- In outer space, the electricity thus generated might be used to power an ion drive or other relatively advanced ways of converting electricity into thrust. Hall effect ion thrusters have flown on several Russian spacecraft and can deliver specific impulses of circa 1800 seconds. Even higher specific impulses (2000 to 4000 seconds) are available from gridded ion engines, typically using xenon as propellant. Such engines have flown on several commercial satellites. In a gridded ion engine, the ions are accelerated by a pair of gridded electrodes, and are then neutralised by electrons emitted by a further component, to prevent a space charge from building up around the satellite, which would otherwise largely neutralise the acceleration being sought.

- In outer space it may be possible to achieve an even higher specific impulse by creating a "balanced" ion engine that ejects equal amounts of positive and negative ions. The ejected ions should then be attracted to each other rather than back towards the spaceship, which is the usual difficulty that an ion engine faces. Particularly attractive ions to use in this context might be H_2^+ and H_2^- since H_2 has the lowest molecular mass of any easily available gas. These ions can therefore be accelerated to a particularly high velocity per unit of applied electric field. The mass of a proton is 938 MeV, so that the speed that either of these ions might reach if accelerated by a 1 MV electric field would be circa 3% of the speed of light, i.e. circa 10^7 ms^{-1}, or if by a 10 kV electric field to circa 10^6 ms^{-1} (i.e. providing a specific impulse of circa 10^5 seconds). Accelerating the ions to this speed is essentially an exercise in taking existing particle accelerator technology and making it as lightweight as possible. Whilst it is not as propellant-efficient as a solar sail (which needs to carry no propellant whatsoever), the amount of propellant such an ion engine might use would be probably be so small that it would not be a material constraint on flight trajectories. Such an engine

powered by a suitable solar power collector might therefore provide substantially higher acceleration than an equivalent solar sail arrangement of equivalent area although of course it would be more complicated in construction.

(d)   Another advantage offered by arrangements according to the present invention is
5   that they may be used to facilitate several of the above means of solar-propulsion in the same vehicle at different times during its journey. The same optical arrangement may be reused within the same flight with any of the above ways of creating thrust. In conjunction with a means of converting solar power into electricity, it can also provide for other electric power requirements for the vehicle (e.g. a commercial satellite will require electric power to function once in orbit). For
10   example, a solar-powered orbital launch vehicle may be created using an optical arrangement in line with the present invention. The optimum use of propellant involves increasing the specific impulse as the vehicle's speed increases. With traditional rocketry, this is usually rather difficult and, in general, the faster a traditional chemical rocket accelerates the better, as the drag imposed by gravity is correspondingly lower. But with solar powered flight, there is a more complex trade-off,
15   since the longer the flight the more the energy that can be collected to provide thrust. Considering the use of solar thermal propulsion as above to launch a vehicle into earth orbit from rest close to the surface of the earth, and assuming for simplicity also that air resistance could be ignored, the following analysis can be made. If the mass of propellant is circa 7 times the mass put into orbit then it appears to be optimal for such a solar powered orbital launch vehicle initially to expel .
20   propellant at a speed of approximately $1,400ms^{-1}$ in a direction that is about 45° (downwards) to the vertical. As the flight progresses and the vehicle speeds up, it appears to be optimal for the propellant to continue to be expelled at circa 45° to the vertical but for the speed at which it is expelled to be increased continuously until the maximum possible expulsion velocity is reached (probably circa 10^4 ms^{-1} using arrangements according to the present invention, and ignoring the
25   possibility of "after-burn"). This approach would appear to require circa 70 kW of power per kg lifted into orbit (assuming 100% efficiency of conversion of sunlight into thrust) and a flight lasting circa 800 seconds. Perhaps twice the power per kg would be needed if the propellant were expelled at a fixed velocity relative to the vehicle, showing the inherent advantages of an engine able to deliver a variable specific impulse. In bright sunlight, each 1 m^2 of solar collector perpendicular to the sun's
30   rays could collect circa 1.4 kW of solar power (in the vicinity of the earth). Each 1 kg of mass lifted into orbit would then, in theory, require circa 50 m^2 of collector aperture area (and an only slightly larger overall mirror surface area with the present invention). NASA has reportedly developed materials that can be used to make robust solar sails that weigh less than 5 gm^{-2}. For solar thermal propulsion engines that are at least, say, 50% efficient in a thermodynamic sense (which is not
35   impossible given the probable relevant input and output temperatures involved in the solar thermal engine), then it would be feasible for a mirror arrangement according to the present invention, in conjunction with a solar thermal propulsion engine, to launch itself, and roughly the same mass again, into earth orbit (albeit that mass would have to include the engine and other elements of the vehicle superstructure). Such a launch methodology has the further advantage of being potentially
40   fully reusable and, if desired, of then being able to travel to most of the rest of the solar system by

reusing the mirror arrangement as a solar sail (or by using it to facilitate electric power generation which then powers an ion engine).

(e)   Of course, a disadvantage that arrangements according to the present invention would potentially present in the context of a solar-powered orbital launch vehicle is that mirrors of the necessary size would generate a very high air resistance if the vehicle were travelling at any reasonable speed within the earth's atmosphere. This would be less relevant if the solar thermal engine could be used to heat up air within the atmosphere (in a manner akin to a jet engine), switching to internally carried propellant on leaving the atmosphere. But, the calculation in (d) suggests that some further improvement in the mass per unit area of the relevant mirrors would probably still be needed before it would be realistic at present to expect to be able to use a solar thermal engine unaided to launch a vehicle into orbit. A more practical suggestion, at the present time, would be for the vehicle to build up speed within the atmosphere using a chemical rocket (or jet engine) and only after leaving the atmosphere to switch to solar thermal propulsion. To reduce vehicle mass it would be desirable for the same engine to be used for both the chemical rocket/jet engine stage and the solar thermal propulsion stage. This launch strategy also implicitly takes advantage of the typically lower specific impulses that chemical rockets/jet engines might generate, which are more suited to use earlier on in such a flight. For example, if chemical rockets were used to reach one-half orbital speed, i.e. circa 3,900 ms^{-1} (a speed that should be fast enough to lift the vehicle out of the earth's atmosphere), the chemical rockets would have delivered one-quarter of the kinetic energy needed to reach orbital velocity. The required area of a solar power collector to provide the solar thermal propulsion component to make up the difference would fall by around 60–75% making a partially solar-powered orbital launch vehicle (that might still be fully reusable) rather more plausibly within the reach of currently available technology. If the chemical rocket imparted a speed of 5,000 ms^{-1} (still less than half the kinetic energy required to reach orbit) then the required power to mass ratio from the solar powered stage falls by nearly another 50%. It should be noted that air resistance is also not necessarily always disadvantageous – the mirrors forming the solar collectors would probably need to be quite flexible to be light enough for this sort of purpose. This means that they might also be able to be used as parachutes on re-entry.

(2)   For terrestrial power generation purposes, arrangements according to the present inventions can be used to concentrate sunlight and make the energy available by similar methods as described in (1)(c) above. An advantage of arrangements according to the present invention is that the solar concentrator can be made of low mass per unit area materials, which should reduce manufacturing cost. For example, mirrors forming the optical arrangement could be embedded within an inflated balloon. If filled with a lighter than air gas then it is only necessary to have three tethers to be able (by changing the lengths of the tethers) to point the concentrator in a wide variety of directions. This would facilitate tracking of the sun, which would be necessary to maximise solar energy production. A large arrangement might favour use of a thermionic power generator over other ways of converting the concentrated sunlight into power.

(3)   Applications envisaged in the applicant's previous patent application PCT/GB01/01161 entitled "Ultra-high resolution imaging devices" are further facilitated using arrangements according to the present invention because these provide alternative ways of

creating ultra-high numerical aperture imaging devices. Such applications include the following (and some others that have already been examined in more detail as above):

- Ultra-high resolution optics, including those that potentially circumvent the Rayleigh resolution criterion, which are particularly attractive for high resolution photolithographic purposes, including semiconductor microchip fabrication.

- Concentration or projection of light or other waves (including potentially other electromagnetic waves or sound waves) or physical entities satisfying equivalent 'ballistic' equations of motion. In a highly rarified atmosphere, individual gas molecules might be expected to behave in this sort of ballistic manner, which may enable the present invention to facilitate the concentration of gas in the upper atmosphere, again potentially facilitating powered flight.

- Structures where the mirrors are not inherently rigid, but are inflated or rotated in operation in order to attain or retain their required shapes.

- Interlinking of optical networking components.

- Variants in which the shapes of the mirrors are further modified to compensate for higher order aberrations by deviating from the aplanatic ideal in such a way that light or other waves (or other physical entities satisfying "ballistic" equations of motion) coming from a circular or far away spherical object primarily falls within a circular shaped image, the circle being smaller than the shape of the image that would be formed by the corresponding ideal aplanatic arrangement.

- Variants which comprise one or more additional mirrors and/or refracting or diffracting surfaces, adapted to exhibit improved aberration characteristics.

Aspects of the present invention will now be described in detail and by way of example with reference to the accompanying drawings, in which:

Figure 1 and 2 are cross-sectional representations of a two-mirror design for an ultra-high resolution imaging device as described in the applicant's previous patent application PCT/GB01/1161.

Figures 3 to 17 are cross-sectional representations of alternative two-mirror embodiments according to the present invention.

Figure 18 is a perspective representation of a solar thermal propulsion arrangement according to the present invention using the two-mirror design of Figure 17.

Figure 19 is a perspective representation of a corresponding arrangement to that shown in Figure 18, employed as a solar sail.

Figure 20 is a perspective representation of an arrangement according to the present invention used to facilitate solar power generation via a tethered balloon structure.

Figures 21 and 22 are perspective views from two different angles of the mirror surfaces of which Figure 17 is a cross-section.

The method of the present invention is directed principally at identifying new ways of positioning a rotationally-symmetric, two-mirror arrangement that is capable of focusing electromagnetic radiation (or other sorts of waves) to almost the thermodynamic upper limit. As the layout is rotationally symmetric, it is possible, without loss of generality determine its structure by

considering a cross-section through the axis of symmetry (say in the xy-plane), with the x-axis being taken to be the axis of symmetry. For a two-mirror layout to exhibit first order aplanatism when creating an image on the plane $x = 0$ and centred on the origin, it is sufficient that the following conditions are satisfied:

5   (a)   that the device is rotationally symmetric around the x-axis, with the object plane (say at $x = f$);

         (b)   that it satisfies the sine criterion; and

         (c)   that all light rays emanating from the point $(f,h,0)$ in the object plane that reach the image plane having travelled in the plane $z = 0$ need to go through a single point in

10   the image plane, say $(0,ZBh,0)$, for all sufficiently small h (B being the degree of magnification the device produces and hence independent of h, and Z being ±1, depending on whether the image is inverted or not).

The reason for sufficiency is that (a) and (c) taken together are equivalent to forming a crisp image (aplanatic of order 1) for rays remaining in a cross-section through the axis, and the further

15 imposition of (b) means (for the right sign of Z) that the device continues to form a crisp image even if the rays do not remain wholly within this cross-section.

Thus the positioning of each consecutive point on each of the two mirrors may be iteratively . determined as follows:

         (a)   At the t'th iteration, the mirrors are positioned so that a light ray starting at exactly the

20   object point $(f, 0)$ will go through the image point $(0, 0)$, after striking the first mirror at $M_1(t) = (m_{1,x}(t), m_{1,y}(t))$ and the second mirror at $M_2(t) = (m_{2,x}(t), m_{2,y}(t))$. The angle that the two mirrors make to the x-axis at the t'th iteration can be found by geometry, given behaviour of light rays when they are reflected off of surfaces. These angles then define the tangents to the two mirrors at this step in the iteration.

25   (b)   The position of $M_2(t+1)$ is found so that if a light ray starts at (f, h), strikes the first mirror at $M_1(t)$ and the second mirror at $M_2(t+1)$ then it passes through $(0, ZBh)$, for a suitable constant B (the magnification of the arrangement), and a suitable sign $Z = ±1$, h small (positive or negative). We apply the additional constraint that $M_2(t+1)$ must be on the tangent to the second mirror as identified in (a), which means that the (unique)

30   position of $M_2(t+1)$ can be found by geometry.

         (c)   The position of $M_1(t+1)$ is found so that if a light ray starts at $(f, 0)$, strikes the first mirror at $M_1(t+1)$ and the second mirror at $M_2(t+1)$ then it passes through $(0, 0)$. Again we apply the additional constraint that $M_1(t+1)$ must be on the tangent to the first mirror as identified in (a), which means that the (unique) position of $M_1(t+1)$ can also

35   be found by geometry.

         (d)   The angles that the mirrors make to the x-axis at the $(t+1)$'th iteration and hence their tangents are then up-dated as per (a), and the iteration repeated.

In the limit as $h \to 0$ this approach defines the shape of two surfaces that together form a perfectly aplanatic (of order 1) imaging mirror arrangement. The mathematics can be restated as

40 follows:

(a) $M_0(t) \equiv \left(m_{0,x}(t), m_{0,y}(t)\right)$ and $M_3(t) \equiv \left(m_{3,x}(t), m_{3,y}(t)\right)$ define the positions of the centres of the object and image planes respectively (so $M_0(t) \equiv (f,0)$, $M_3(t) \equiv (0,0)$ say).

(b) $d_i(t)$ (for $i = 0, ..., 2$) is the angle that a ray from $M_i(t)$ to $M_{i+1}(t)$ makes to the x-axis, i.e.

$$d_i(t) = \arctan\left(\frac{m_{i+1,y}(t) - m_{i,y}(t)}{m_{i+1,x}(t) - m_{i,x}(t)}\right)$$

(c) $p_i(t)$ (for $i = 0, ..., 2$) is the distance between $M_i(t)$ and $M_{i+1}(t)$, i.e.

$$p_i(t) = \sqrt{\left(m_{i+1,x}(t) - m_{i,x}(t)\right)^2 + \left(m_{i+1,y}(t) - m_{i,y}(t)\right)^2}$$

(d) $a_i(t)$ is the angle that a tangent to the ith surface makes to the x-axis, taking $a_0(t)$ and $a_3(t)$ to be the angles that the object and image planes make to the x-axis (being 90° for all t for the surfaces to be rotationally symmetric about the x-axis), i.e. for reflection (for $i = 1$ and 2):

$$a_i(t) = \frac{d_i(t)}{2} + \frac{d_{i-1}(t)}{2}$$

(e)   The values of $m_{i,x}(0)$ and $m_{i,y}(0)$ (for $i = 1$ and 2) are chosen so that the resulting mirror layout satisfies the sine criterion. For a far away source (say along the negative x-axis, say $f = -10^9$) we can without loss of generality set b, a scale parameter, equal to unity, setting $B = b/p_0(0) = 1/p_0(0)$. The sine criterion is then satisfied if:

$$m_{1,y}(0) = \pm\frac{m_{2,y}(0)}{\left(m_{2,x}(0)^2 + m_{2,y}(0)^2\right)^{1/2}}$$

(f)   It is possible to iterate either from shallower angles to more oblique angles, or vice versa, and to switch between the two by using as seed values later iterated results and reversing the sign of h. If the iteration is started from highly oblique angles then $m_{2,x}(0)$ may be chosen equal to a small number close to zero, say 10^{-9}, and we can choose $m_{1,x}(0) = q_1$ and $m_{2,y}(0) = q_2$, where q_1 and q_2 are arbitrary real numbers (positive or negative). Then $m_{1,y}(0)$ would need to be ±1 for the initial parameters to satisfy the sine criterion. Without loss of generality, $m_{1,y}(0)$ may be chosen to be -1.

(g)   The choice of the sign Z is made so that the sine criterion remains satisfied as t changes. Only one choice will work depending on the layout, for the two-mirror layouts being analysed here and, if $m_{1,y}(0) = -1$, then the correct choice will generally be $Z = \mathrm{sgn}(m_{2,y}(0))$.

(h)   The values of $M_i(t)$ are then updated as follows for a small value of h (which can also be positive or negative):

$$M_i(t+1) \equiv \begin{pmatrix} m_{i,x}(t+1) \\ m_{i,y}(t+1) \end{pmatrix} = M_i(t) + w_i\begin{pmatrix} \cos(a_i(t)) \\ \sin(a_i(t)) \end{pmatrix}h$$

where $r_{i-1}(t) = \sin\left(a_{i-1}(t) - d_{i-1}(t)\right)$ $s_i(t) = \sin\left(a_i(t) - d_{i-1}(t)\right)$ and where

$$w_2 = \frac{p_1 r_0}{p_0 s_2} \quad w_1 = -ZB\frac{p_1 s_3}{p_2 r_1}$$

(i)   The iteration is ended no later than when light rays would cease to be able to pass freely through the mirror arrangement, after it has been rotated as in (j).

(j)   The complete, three-dimensional mirror surfaces are found by rotating the curves produced above around the x-axis.

The visual appearance and characteristics of mirror layouts defined according to the above iterative process will vary according to the signs of q_1, q_2 and h. The applicant has found that the visual appearance and characteristics of the mirror layouts will also normally depend on whether $abs(q_2)$ is larger or smaller than unity., In most instances, there is a discontinuity in the feasible angle ranges that the layouts permit rays to strike the image plane if $abs(q_2)$ is altered from being slightly below 1 to being slightly above 1. Such a discontinuity exists in 6 of the 8 possible combinations of signs of q_1, q_2 and h. The only arrangements where there is no such discontinuity are those where q_1 is negative and q_2 is positive. Thus the above iterative formulae in principle describe 14 possible classes of mirror layout, depending on the sign of q_1, q_2 and h and (unless q_1 is negative and q_2 is positive) whether $abs(q_2)$ is smaller or larger than unity. Within each class, there are further variations available by changing the values of q_1, q_2 subject to each retaining the sign appropriate to the respective class definition. The above approach differs from the method described in PCT/GB01/01161 in several respects, including:

- The description and figures contained in PCT/GB01/01161 all involve iterations which, if restated in the above form, would involve seeding the iterative process with q_1 negative, q_2 positive and h positive, which produces mirror arrangements of the sort illustrated in Figures 1 and 2. It can be seen that the visual appearance (and the behaviour of the relevant ray traces) of most of the new types of mirror layout produced according to the present invention are significantly different in nature to those previous arrangements. For example, in 8 of the 14 examples of new arrangements, the focal plane is between the two mirrors, rather than being beyond the second (inner) mirror as was the case in the arrangements of Figures 1 and 2 and as described in PCT/GB01/01161 where the method indicated that the first mirror, M_1, would be nearest to the object and the second mirror, M_2, would be nearest to the image. A high proportion of the new mirror layouts illustrated in Figures 3 to 16 do not satisfy this requirement. In 4 of the new arrangements, the focal plane is also closer to the object than either mirror.

- Unexpectedly, a number of the new arrangements appear potentially much more efficient than those in PCT/GB01/01161 for solar energy purposes, because they have much smaller ratios of surface area to aperture area. This applies in particular to the arrangements illustrated in Figures 3 and 4, and also to a lesser extent, to those illustrated in Figures 5 and 6. The arrangement of these more efficient layouts was not predicted in the description of the arrangements in PCT/GB01/01161.

- The description of how to seed the original iterative formulae in PCT/GB01/01161 indicated that $m_{1,x}(0)$ and $m_{2,x}(0)$ should only differ by an infinitesimal amount for the shallowest feasible ray angle falling onto the image plane. This requirement is met by the class of mirror configurations originally described in PCT/GB01/01161, where q_1 is negative, q_2 is positive and h is positive (illustrated in Figures 1 and 2), but is not generally met by the new arrangements according to the present invention. Surprisingly, there is one exception, which occurs where q_1 is negative, q_2 is

negative, h is negative <u>and</u> abs(q_2) is less than one. This type of arrangement is illustrated in Figure 9. Interestingly and unexpectedly, the resulting arrangement is visually similar to the two-mirror arrangements first described in PCT/GB01/01161, although obtained via a different route.

5   - The description in PCT/GB01/01161 also indicated that there were *two* parameters that defined the shape of the mirror layout contained in PCT/GB01/01161, which it took as $m_{2,x}(0) = k$ and $m_{2,x}(0) = -q$. The present analysis provides for variation in accordance with *three* relevant parameters, since it introduces a further dependency on the sign of h. The two parameters q and k in PCT/GB01/01161 carry out a similar role to q_1 and q_2 in the above analysis. The disclosure in PCT/GB01/01161 only envisaged instances where k was positive and the sign of q was negative.

10   These correspond to the same type of layouts as those shown in Figures 1 and 2 where q_1 is negative and q_2 is positive.

           - PCT/GB01/01161 was primarily directed towards high-resolution optics, particularly for high precision photolithography. The type of high numerical aperture imaging arrangement described in PCT/GB01/01161 is particularly suited to such purpose because all of the optical components are on

15   the same side of the surface onto which the image is being projected. A particular subset of the sort of layout illustrated in Figure 1, that was also given prominence in PCT/GB01/01161, was the arrangement where the two mirrors can be joined up to form a single surface.

           The iterative process according to the method described in the present invention provides for alternative and additional arrangements to those set out in PCT/GB01/01161 in that it allows for

20   each of the signs of q_1, q_2 and h to be changed to be either positive or negative and takes account of arrangements in which abs(q_2) can be larger or smaller than unity, leading to unexpected and unanticipated additional possible types of two-mirror layouts all of which, in principle, may be able to approach close to the thermodynamic upper limit, in that they permit rays to strike the image plane from highly oblique angles. A selection of these new arrangements according to the present invention

25   is illustrated in Figures 3 to 17.

           In each of Figures 1 to 17, the solid lines are cross-sections of the mirrors themselves, and the dotted lines are the paths of light rays from the object to the image passing through extremities of the mirror arrangement. One extremity is the ultra-highly-oblique ray that effectively defines the start of the iteration process referred to above. The other extremity is the upper limit in accordance with step (i) in

30   the iteration. Clearly, it would be possible to limit the iteration to a smaller range of angle spans by starting the iteration later or finishing it sooner than implied in the example Figures.

           The original type of mirror arrangement referred to in PCT/GB01/01161 normally has a relatively high coverage of possible angle spans, and a relatively low second order aberration factor. The latter factor assesses the extent to which, say, light from the rim of the sun's outline in the sky would not fall

35   exactly where the thermodynamic optimum would require (i.e. where it would fall if the mirror arrangement were aplanatic to higher than 1st order). For an ultra-high resolution imaging device, it is important that image aberration is kept as low as possible. For solar energy purposes, if the aberration factor is material, it is possible to improve the concentration characteristics of the mirror layout either by adjusting modestly the iteration process (so that circular objects fall more precisely

40   on the same circle throughout the iteration process) or by adding more surfaces at which the light

is deflected as it passes from object to image. The equivalent characteristics for the other types of layout will depend on the precise values of q_1 and q_2 used to seed the iterative process.

Further modifications to the formulae according to the present invention can also be introduced by making equivalent variations to those previously described in PCT/GB01/01161 to handle refractive or diffractive arrangements. These involve changing the formulae used to define $a_i(t)$ in (d) and w_1 and w_2 in (h) to reflect how light rays are deflected at a refractive or diffractive surface rather than a reflective surface.

Likewise, equivalent adaptations to those set out in PCT/GB01/01161 can be made to handle the inclusion of additional reflecting, refracting or diffracting surfaces to improve the aberration characteristics of the new arrangements according to the present invention.

For convenient comparison of relevant parameters and characteristics of the original two-mirror layout (of PCT/GB01/01161) with the new arrangements provided according to the present invention, Figures 1 and 2 (representative of the original arrangements) and 3 to 16 have been derived by choosing standardised values of ±2 and ±0.2 (or ±3 when considering cases where abs(q_2) is larger than b, i.e. unity) respectively for the seed parameters. Table 1 provides a numeric comparison of the characteristics:

Figure	q_1	q_2	Sign of h	effective aperture area	aberration factor	mirror surface area
1	-2	0.2	+	90%	0.020	2.86
2	-2	3	+	27%	0.007	43.01
New arrangements:						
3	2	-0.2	-	96%	0.059	1.03
4	2	0.2	+	96%	0.079	1.06
5	2	0.2	-	89%	0.017	1.56
6	2	-0.2	+	50%	0.021	2.74
7	-2	0.2	-	88%	0.038	3.24
8	-2	-0.2	+	85%	0.077	3.51
9	-2	-0.2	-	41%	0.013	7.81
10	2	3	+	85%	0.008	17.46
11	2	3	-	29%	0.009	41.80
12	2	-3	+	77%	0.007	31.57
13	2	-3	-	77%	0.005	16.39
14	-2	3	-	57%	0.012	23.46
15	-2	-3	+	54%	0.035	26.91
16	-2	-3	-	80%	0.002	32.71

TABLE 1

Note:

In the above table the characteristics on the right hand side are calculated as follows:

effective aperture area = area of first mirror perpendicular to sun's rays, expressed as a proportion of the maximum possible were the angle span of rays falling onto the image plane to be the complete range from wholly oblique to exactly perpendicular to the image plane. The higher this is, the closer to the thermodynamic upper temperature limit such a concentrator can approach.

aberration factor = average maximum second order degree of aberration for sunlight in the vicinity of the earth (i.e. for a far away source subtending approximately a semi angle of 0.267°). The degree of aberration is calculated using the formulae described in PCT/GB01/01161, i.e. it is how far away from the aplanatic ideal that an extreme radial ray from the edge of the sun on average strikes the image plane divided by the distance of this aplanatic ideal imaging point from the centre of the image plane.

mirror surface area = the total surface area of the two mirrors combined as a multiple of the effective aperture area. The smaller is this figure, the less is the mirror surface area required per unit of power delivered, and therefore all other things being equal, the less the mirror arrangement will weigh.

Figures 1 and 2 and Figures 3 to 16 are plots of the cross-sections through the axis of rotation of different types of two mirror imaging layouts that focus objects infinitely far away along the negative x-axis, are aplanatic and have the potential to achieve a very high numerical aperture because the permit rays to strike the image plane at highly oblique angles, the different types being characterised by different types of choices concerning three parameters involved in the iterative process referred to above.

Figure 17 is another example of the type of mirror layout illustrated in Figure 3 but with different initial parameters used in the iterative formulae used to identify how the two mirrors are positioned.

For most of the proposed uses of the present invention, it is unlikely to be desirable for $abs(q_2)$ to be larger than unity, since it would significantly increase the overall surface area of the mirrors, and hence the weight of any corresponding solar power collector. The original arrangements of Figure 1 and Figure 2 (even more so) are also relatively undesirable for such purposes because they have a relatively high ratio of actual mirror area to effective collector aperture perpendicular to the sun's rays, increasing the weight of the collector per unit power collected. The two lightest mirror layouts shown, and therefore the ones most likely to be helpful for most of the proposed uses of the present invention, are those in Figures 3 and 4. However, layouts akin to Figure 4 would have the disadvantage that the sunlight would pass very close to the positive x-axis on its way towards the image. Any exhaust gases propelled out of a solar thermal engine used in conjunction with such a mirror arrangement are likely to be ejected approximately along this axis. Indeed, it may be best to force them to be ejected along this axis, by some sort of exhaust guide, perhaps again made out of a very lightweight flexible material akin to the substrate underlying the mirrors. Thus with layouts akin to Figure 4, many of the incoming light rays might be fouled by the exhaust gases themselves or this exhaust guide. Layouts akin to Figure 3 are therefore likely to be preferred. The rays in this variant do not cross the positive x-axis. Such an arrangement also offers a slightly lower surface area as a proportion of effective collector aperture, and better aberration characteristics without altering the effective aperture area.

Changing the values of q_1, q_2 but not their signs (or whether the absolute value of q_2 is smaller or larger than unity) produces mirror layouts that have visual similarities to the one shown in Figure 3 but are somewhat different shapes. Possible disadvantages of using values of $q_1 = 2$ and $q_2 = -0.2$ are that the larger mirror is some way away from the image. For a solar-powered orbital launcher, which could be hundreds of metres in diameter, the further away the mirror is, the longer would need to be the wire or wires joining the engine to the mirror. This might therefore increase the masses of these wires. A more compact arrangement may be preferred. If the vehicle is to travel in the direction of its axis then the solar thermal rocket exhaust needs to escape through the hole in the centre of the larger mirror, which subtends quite a small angle in this arrangement. This angle would also be larger if $abs(q_2)$ were larger and q_1 were smaller. Of course, such parameter changes also alter other characteristics of the mirror pair, in some instances detrimentally, so some trade-off is likely to be required. For example, if Figure 3 is altered to use q_1 = 0.7 and $q_2 = -0.3$ then the mirror layout becomes as shown in Figure 17. The average aberration factor improves to 0.020, but the effective aperture area falls to 91% and the mirror surface area as

a multiple of the effective aperture area rises to 1.13. Reducing q_1 also makes the smaller mirror closer to the image plane, increasing the possibility that it might overheat.

The present invention provides for new applications of the novel high numerical imaging layouts described here including their use as solar sails, their use to provide power for a balanced ion drive,
5   their use to provide a solar-powered orbital launch vehicle, their use for several different purposes at different times during the same flight, their use in a tethered balloon arrangement for generating electric power, and their use in a solar thermal propulsion context with the solar thermal propulsion engine incorporating the equivalent of "after-burn".

Figure 18 is a perspective view of an embodiment used to provide solar thermal propulsion.
10   The two (lightweight) mirrors (1a) and (1b) are jointly arranged according to the iterative process provided in the present invention as described above (in this embodiment, as in Figures 19 and 20 their layout is as shown in Figure 17). Sunlight (1h) is concentrated via these two mirrors onto a small area (1c) (not here drawn to scale, as in the vicinity of the earth this would be approximately 1/200th of the radius of the mirror (1a)). Here it heats up a propellant to a high temperature. The
15   propellant is then expelled through one or more nozzles (1d). It may be helpful to have a guide (1e) to ensure that the expelled propellant does not damage the larger mirror (1a). Payload and propellant etc would be carried somewhere within the overall rocket superstructure (1f). For a solar orbital launch vehicle, to avoid excessive air resistance at launch, the mirrors could be stowed in a suitable container (1g) within the vehicle superstructure, with the rocket initially being powered by a
20   conventional rocket to build up some speed and to propel the vehicle beyond the atmosphere.

Figure 19 is a perspective view of an embodiment used as a solar sail. The two (lightweight) mirrors (2a) and (2b) are arranged, as in Figure 18, according to the present invention. Sunlight (2d) is concentrated via these two mirrors onto a small area. Instead of placing a solar thermal propulsion engine there, the sunlight would be deflected (by roughly 90° to the direction of the
25   incoming sunlight) by a suitable additional mirror arrangement (2c), of which the easiest to envisage is a parabolic mirror with a focal point positioned at the same place as the focal point of the two mirror arrangement (2a) and (2b).

Figure 20 is a perspective view of an embodiment used to facilitate solar power generation via a tethered balloon structure. The two (lightweight) mirrors (3a) and (3b) are arranged, as in
30   Figure 18, according to the present invention. The mirrors are embedded within a balloon. In this embodiment the balloon is spherical with three chambers (3c), (3d) and (3e), with the middle one (3d) being bordered by the mirrors (3a) and (3b). The pressure in (3d) would be higher than in (3c) or (3e) which in turn would be higher than outside, so that the shape of the arrangement remains as shown in the figure. The gas within the balloon would be sufficiently lighter than air for the whole
35   arrangement to be buoyant. Tethers (3f) would then be joined between the balloon and the ground (3g); by altering the length of the tethers the arrangement would be kept pointed so that sunlight (3h) is falling onto the mirror arrangement parallel to its axis of rotation.

Figure 21 and Figure 22 are perspective views from different angles of the mirror arrangement shown in cross-section in Figure 17 and as in the example applications illustrated in
40   Figures 18, 19 and 20.

It will be appreciated that arrangements according to the present invention may also be adapted for use in applications and with additional or modified components corresponding to those described in PCT/GB01/01161.